A NOTE ON WETTING TRANSITION FOR GRADIENT FIELDS

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ABSTRACT. We prove existence of a wetting transition for two types of gradient fields: 1) Continuous SOS models in any dimension and 2) Massless Gaussian model in dimension 2. Combined with a recent result showing the absence of such a transition for Gaussian models above 2 dimensions [5], this shows in particular that absolute-value and quadratic interactions can give rise to completely different behavior.

1. Introduction

In several recent papers [3, 9, 2, 1, 6], the question has been raised whether the 2 dimensional massless Gaussian model exhibited a wetting transition. It is well-known that the Gaussian field in 2D is delocalized, with a logarithmically divergent mean height, but that the introduction of an arbitrarily weak self-potential favoring height 0 is enough to localize it, in the sense that the mean height remains finite [10, 2]; this result has recently been extended to a class of non Gaussian models in a stronger form, showing in particular existence of exponential moments for the heights [9] and exponential decay of covariances [12]. For higher dimensional model, the field is already localized without pinning potential, but the introduction of such a potential turns the algebraic decay of the covariances into an exponential one. On the other hand, a Gaussian field with a positivity constraint ("surface above a hard-wall") exhibits entropic repulsion: The average height diverges like $\log N$ in 2D [8] and $\sqrt{\log N}$ in higher dimensions [4] (N being the linear size of the box). When both a positivity constraint and a pinning potential are present ("surface above an attractive hard wall"), there is a competition between these two effects. If there exists a (non zero) critical value for the strength of the pinning potential above which the interface is localized, but below which it is repelled by the wall, we say that the model exhibits a wetting transition. That such a transition occurs in a wide class of 1D model is well-known, see e.g. [11, 5]. It was recently shown in [5] that the Gaussian model in dimensions 3 or higher does not display a wetting transition: The interface is always localized. The physically important case of the 2D model (describing a 2D interface in a 3D medium) remained however open.

In the present note, we prove that the 2D Gaussian field does exhibit a wetting transition; in fact the proof applies to any strictly convex interaction, see below. We also prove that the continuous SOS model has such a transition in *any* dimension, thus showing that the choice of the interaction can greatly affect the physics of the system. Our proofs are based on a variant of a beautiful and simple argument of Chalker [7], who proved the existence of a wetting transition in the discrete SOS model in dimension 2.

2. Results

We consider a class of gradient models with single spin-space $\mathbb{R}^+$, i.e. modeling surfaces above a hard wall. Let Λ_N be the cube of side N centered at the origin, and $\Psi : \mathbb{R} \to \mathbb{R}$

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an even function to be specified later; we consider the following Hamiltonian

$$H_N^{0,a,b}(\phi) = H_{0,N}^0(\phi) + V_N^{a,b}(\phi)\,,$$

where

$$H_{0,N}^0(\phi) = \sum_{\langle x,y\rangle\subset\Lambda_N} \Psi(\phi_x-\phi_y) \;+\; \sum_{\substack{\langle x,y\rangle \\ x\in\Lambda_N,\, y\notin\Lambda_N}} \Psi(\phi_x)\,,$$

$$V_N^{a,b}(\phi) = -b\sum_{x\in\Lambda_N} 1_{\{\phi_x\,\leqslant\, a\}}\,,\quad a,b>0\,,$$

($\langle x,y\rangle$ denotes a pair of nearest neighbour sites). The corresponding Gibbs measure (on $(\mathbb{R}^+)^{\Lambda_N}$) is then given by

$$\mu_N^{0,+,a,b}(\,\mathrm{d}\phi) = \frac{e^{-H_N^{0,a,b}(\phi)}}{Z_N^{0,+,a,b}}\prod_{x\in\Lambda_N}\mathrm{d}\phi_x\,.$$

As in the pure pinning problem (i.e. without a wall) [9], the relevant parameter is $\varepsilon(a,b) = ae^b$ and not both a and b separately. As usual, we introduce the *δ-pinning* limit, which is the model described by the measure

$$\mu_N^{0,+,\varepsilon}(\,\mathrm{d}\phi) = \lim_{\substack{a\to0\\ \varepsilon(a,b)=\varepsilon}} \mu_N^{0,+,a,b}(\,\mathrm{d}\phi) = \frac{e^{-H_{0,N}^0(\phi)}}{Z_N^{0,+,\varepsilon}}\prod_{x\in\Lambda_N}(\,\mathrm{d}\phi_x+\varepsilon\delta_0(\,\mathrm{d}\phi_x))\,.$$

Note that $\mu_N^{0,+,\varepsilon}$ can be written more explicitly as

$$\mu_N^{0,+,\varepsilon}(\,\mathrm{d}\phi) = \sum_{A\subset\Lambda_N}\varepsilon^{|A|}\frac{Z_{\Lambda_N\setminus A}^{0,+}}{Z_N^{0,+,\varepsilon}}\,\mu_{\Lambda_N\setminus A}^{0,+}(\,\mathrm{d}\phi)\,,$$

where

$$Z_{\Lambda_N\setminus A}^{0,+} = \int e^{-H_{0,N}^0(\phi)}\prod_{x\in\Lambda_N\setminus A}\mathrm{d}\phi_x\prod_{y\in A}\delta_0(\,\mathrm{d}\phi_y)\,,$$

and

$$\mu_{\Lambda_N\setminus A}^{0,+}(\,\mathrm{d}\phi) = (Z_{\Lambda_N\setminus A}^{0,+})^{-1}\,e^{-H_{0,N}^0(\phi)}\prod_{x\in\Lambda_N\setminus A}\mathrm{d}\phi_x\prod_{y\in A}\delta_0(\,\mathrm{d}\phi_y)$$

is the Gibbs measure on $\Lambda_N\setminus A$ with 0 boundary condition outside.

Remark: Here and everywhere else in this note, the integrals are restricted to the positive real axis, so we do not write this condition explicitly.

A quantity of interest is the density of *pinned sites*, i.e. of those sites where the interface feels the effect of the pinning potential; it is defined as

$$\rho_N(a,b) = |\Lambda_N|^{-1}\mu_N^{0,+,a,b}(\nu_N(\phi))\,,$$

where $\nu_N(\phi) = \sum_{x\in\Lambda_N} 1_{\{\phi_x\,\leqslant\, a\}}$. We also write $\rho(a,b) = \lim_{N\to\infty}\rho_N(a,b)$. The corresponding quantities in the δ-pinning limit are denoted $\rho_N(\varepsilon)$, $\rho(\varepsilon)$ (measuring the density of sites exactly at height 0). ρ will play the role of an order parameter for the wetting transition.

Our results can then be stated as follows.

Theorem 2.1. *Let $\Psi(x) = |x|$, $d \geqslant 1$. Suppose that $ae^b < (2d)^{-1}$, then there exist two constants $C_1(a,b,d)$ and $C_2(a,b,d)$ such that, for any $M > C_1 N^{d-1}$,*

$$\mu_N^{0,+,a,b}(\nu_N(\phi) > M) \leqslant e^{-C_2 M}.$$

In particular, $\rho(a,b) = 0$.

Theorem 2.2. *Consider δ-pinning in the two cases:*

1. $\Psi(x) = |x|$, $d \geqslant 1$, $\varepsilon < e^{-2d}$;
2. $\Psi(x) = \frac{1}{2}x^2$, $d = 2$, $\varepsilon < \varepsilon_0$ *for some small positive number* ε_0.

Then there exist two constants C_3 and C_4 depending on ε, d in the first case and only on ε in the second case, such that, for any $M > C_3 N^{d-1}$,

$$\mu_N^{0,+,\varepsilon}(\nu_N(\phi) > M) \leqslant e^{-C_4 M}.$$

In particular, $\rho(\varepsilon) = 0$ in both cases.

We recall that it is not hard to prove that $\rho > 0$ when the pinning is strong. For example, in the δ-pinning case, we can proceed in the following way. Since

$$|\Lambda_N|^{-1} \log \frac{Z_N^{0,+,\varepsilon}}{Z_N^{0,+,0}} = \int_0^\varepsilon \frac{1}{\hat{\varepsilon}} \rho_N(\hat{\varepsilon})\, \mathrm{d}\hat{\varepsilon},$$

the result follows from $Z_N^{0,+,\varepsilon} \geqslant \varepsilon^{|\Lambda_N|}$ and the existence of a constant C such that $Z_N^{0,+,0} \leqslant C^{|\Lambda_N|}$. To prove the latter inequality one can consider a shortest self-avoiding path ω on $\mathbb{Z}^d$ starting at some site of $\partial\Lambda_N$ and containing all the sites of Λ_N, and using $H_{0,N}^0(\phi) \geqslant \sum_{n=1}^{|\omega|-1} \Psi(\phi_{\omega_n} - \phi_{\omega_{n+1}})$.

The above results imply the existence of a wetting transition in these models[1]. Together with the result of [5] that in the Gaussian model in $d \geqslant 3$ there is *no* wetting transition, the first part of Theorem 2.2 shows a radical difference of behavior between the Gaussian and the SOS interactions.

Remark: 1. It is not difficult to see, looking at the proofs, that our theorems remain true if we replace the SOS interaction $\Psi(x) = |x|$ with any concave, even function, and the Gaussian interaction $\Psi(x) = \frac{1}{2}x^2$ with any even, convex Ψ such that $1/c \geqslant \Psi''(x) \geqslant c$ for some $c > 0$ and all x.
2. Even though the present work provides a proof of the wetting transition in the models considered, several important issues remain completely open. In particular, it would be most desirable to have a pathwise description of the field in both the localized and repelled regimes, i.e. a proof that $\rho > 0$ implies finiteness of the mean height of any fixed spin in the thermodynamic limit (if possible with estimate on the tail and exponential decay of correlations), and a proof that $\rho = 0$ implies that the mean height of any fixed spin diverges (if possible with estimates on the rate).

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[1] In the δ-pinning case, it can easily be seen that ρ is monotonous in ε, so that there is a single critical value.

3. Proof of Theorem 2.1

Let $M>0$; following [7], we introduce the set $\mathcal{B}_M=\{\phi\,:\,\nu_N(\phi)\geqslant M\}$, and the set

$$\mathcal{C}_M=\{\phi\,:\,\sum_{x\in\Lambda_N}1_{\{\phi_x\,\leqslant\,2a\}}\geqslant M\}\,.$$

Since $\mathcal{B}_M\subset\mathcal{C}_M$, the first claim immediately follows from the estimate on conditional probabilities

$$\mu_N^{0,+,a,b}(\mathcal{B}_M|\mathcal{C}_M)\leqslant e^{-C_2\,M}\,,\quad M>C_1N^{d-1}\,. \tag{3.1}$$

Moreover, $\rho(\varepsilon)=0$ will follow from this and the obvious bound

$$\rho_N\leqslant\frac{M}{N^d}+\mu_N^{0,+,a,b}(\mathcal{B}_M)\,,$$

by choosing M such that $N^d\gg M\gg N^{d-1}$.

We turn to the proof of (3.1). We define a map $\mathfrak{T}$ from $\mathcal{C}_M$ onto $\mathcal{B}_M$ by

$$(\mathfrak{T}\phi)_x=\begin{cases}\phi_x & \text{if } \phi_x\leqslant a\,,\\ \phi_x-a & \text{otherwise.}\end{cases}$$

If we write $e^{-V_N^{a,b}}=1_{\{\phi_x>a\}}+e^b1_{\{\phi_x\,\leqslant\,a\}}$ and expand the corresponding products, we have

$$\begin{aligned}\mu_N^{0,+,a,b}(\mathcal{C}_M)&=\int\frac{e^{-H_N^{0,a,b}(\phi)}}{Z_N^{0,+,a,b}}1_{\{\phi\in\mathcal{C}_M\}}\prod_{x\in\Lambda_N}\mathrm{d}\phi_x\\ &=\sum_{\substack{A\subset\Lambda_N\\|A|\,\geqslant\,M}}\sum_{B\subset A}e^{b|B|}\int\frac{e^{-H_N^{0,a,b}(\phi)}}{Z_N^{0,+,a,b}}\prod_{x\in B}1_{\{\phi_x\,\leqslant\,a\}}\,\mathrm{d}\phi_x\prod_{y\in A\setminus B}1_{\{a<\phi_y\,\leqslant\,2a\}}\,\mathrm{d}\phi_y\prod_{z\in\Lambda_N\setminus A}1_{\{2a<\phi_z\}}\,\mathrm{d}\phi_z\,.\end{aligned}$$

Now, observe that

$$H_{0,N}^0(\phi)\leqslant H_{0,N}^0(\mathfrak{T}\phi)+da|\partial\Lambda_N|+2da|B|$$

($\partial\Lambda_N$ being the set of $x\in\Lambda_N$ neighbouring a site $y\notin\Lambda_N$). After the change of variables $\widetilde{\phi}_x=(\mathfrak{T}\phi)_x$, we have

$$\begin{aligned}&\mu_N^{0,+,a,b}(\mathcal{C}_M)\\ &\geqslant e^{-da|\partial\Lambda_N|}\sum_{\substack{A\subset\Lambda_N\\|A|\,\geqslant\,M}}\sum_{B\subset A}\left(e^{-2da}e^b\right)^{|B|}\int\frac{e^{-H_{0,N}^0(\widetilde{\phi})}}{Z_N^{0,+,a,b}}\prod_{x\in A}1_{\{\widetilde{\phi}_x\,\leqslant\,a\}}\,\mathrm{d}\widetilde{\phi}_x\prod_{y\in\Lambda_N\setminus A}1_{\{a<\widetilde{\phi}_y\}}\,\mathrm{d}\widetilde{\phi}_y\\ &=e^{-da|\partial\Lambda_N|}\sum_{\substack{A\subset\Lambda_N\\|A|\,\geqslant\,M}}e^{b|A|}\left(e^{-2da}+e^{-b}\right)^{|A|}\int\frac{e^{-H_{0,N}^0(\widetilde{\phi})}}{Z_N^{0,+,a,b}}\prod_{x\in A}1_{\{\widetilde{\phi}_x\,\leqslant\,a\}}\,\mathrm{d}\widetilde{\phi}_x\prod_{y\in\Lambda_N\setminus A}1_{\{a<\widetilde{\phi}_y\}}\,\mathrm{d}\widetilde{\phi}_y\\ &\geqslant e^{-da|\partial\Lambda_N|}\left(e^{-2da}+e^{-b}\right)^M\ \mu_N^{0,+,a,b}(\mathcal{B}_M)\,,\end{aligned}$$

where we used $e^{-2da}+e^{-b}>1$, which follows from $ae^b<(2d)^{-1}$. This proves (3.1).

4. Proof of Theorem 2.2

The proof is very similar. Let $M > 0$ and define $\mathcal{B}_M$ as in the previous proof (but remember that now ν_N is the number of sites with height equal to 0). We also need a set analogous to the set $\mathcal{C}_M$ of the previous section:

$$\mathcal{D}_M = \{\phi \,:\, \sum_{x\in\Lambda_N} 1_{\{\phi_x \leqslant 1\}} \geqslant M\}\,.$$

We are going to show that

$$\mu_N^{0,+,\varepsilon}(\mathcal{B}_M|\mathcal{D}_M) \leqslant e^{-C_4 M}\,, \quad M > C_3 N^{d-1}\,. \tag{4.2}$$

As in the previous theorem, (4.2) is sufficient to prove our claims.

To prove (4.2) define the map

$$(\mathfrak{S}\phi)_x = \begin{cases} \phi_x - 1 & \text{if } \phi_x > 1 \\ 0 & \text{otherwise} \end{cases}$$

from $\mathcal{D}_M$ onto $\mathcal{B}_M$. Note that $\mu_N^{0,+,\varepsilon}(\mathcal{D}_M)$ can be written

$$\sum_{\substack{A\subset\Lambda_N\\ |A|\geqslant M}} \sum_{B\subset A} \varepsilon^{|B|} \int \frac{e^{-H^0_{0,N}(\phi)}}{Z_N^{0,+,\varepsilon}} \prod_{x\in A\setminus B} 1_{\{\phi_x \leqslant 1\}}\,\mathrm{d}\phi_x \prod_{y\in\Lambda_N\setminus A} 1_{\{1<\phi_y\}}\,\mathrm{d}\phi_y \prod_{z\in B}\delta_0(\,\mathrm{d}\phi_z)\,. \tag{4.3}$$

Let us first discuss the simpler case $\Psi(x) = |x|$, $d \geqslant 1$. We have

$$H^0_{0,N}(\phi) \leqslant H^0_{0,N}(\mathfrak{S}\phi) + d|\partial\Lambda_N| + 2d|A|\,,$$

and therefore, letting $\widetilde{\phi}_x = (\mathfrak{S}\phi)_x$ and integrating over the variables ϕ_x, $x \in A\setminus B$,

$$\begin{aligned}
\mu_N^{0,+,\varepsilon}(\mathcal{D}_M) &\geqslant e^{-d|\partial\Lambda_N|} \sum_{\substack{A\subset\Lambda_N\\ |A|\geqslant M}} \sum_{B\subset A} e^{-2d|A|}\,\varepsilon^{|B|} \int \frac{e^{-H^0_{0,N}(\widetilde{\phi})}}{Z_N^{0,+,\varepsilon}} \prod_{x\in\Lambda_N\setminus A} \mathrm{d}\widetilde{\phi}_x \prod_{y\in A}\delta_0(\,\mathrm{d}\phi_y) \\
&= e^{-d|\partial\Lambda_N|} \sum_{\substack{A\subset\Lambda_N\\ |A|\geqslant M}} \varepsilon^{|A|} e^{-2d|A|} \left(1+\frac{1}{\varepsilon}\right)^{|A|} \frac{Z^{0,+}_{\Lambda_N\setminus A}}{Z_N^{0,+,\varepsilon}} \\
&\geqslant e^{-d|\partial\Lambda_N|}(1+e^{-2d})^M\,\mu_N^{0,+,\varepsilon}(\mathcal{B}_M)\,,
\end{aligned}$$

where we have used the assumption $\varepsilon < e^{-2d}$. This proves (4.2).

Let us now turn to the case $\Psi(x) = \frac{1}{2}x^2$, $d = 2$. Writing $W = A \cup {\Lambda_N}^c$, we have the estimate

$$H^0_{0,N}(\phi) \leqslant H^0_{0,N}(\mathfrak{S}\phi) + 2|\partial\Lambda_N| + 8|A| + 2\sum_{x\in\partial W}\sum_{\substack{y\notin W\\ y\sim x}} (\mathfrak{S}\phi)_y\,.$$

Let us use the short-hand notation $\mathcal{X}(\phi) = 2\sum_{x\in\partial W}\sum_{y\notin W,\,y\sim x}\phi_y$. Inserting this estimate in (4.3) and changing variables to $\widetilde{\phi}_x = (\mathfrak{S}\phi)_x$, we obtain

$$\mu_N^{0,+,\varepsilon}(\mathcal{D}_M) \geqslant e^{-2|\partial\Lambda_N|} \sum_{\substack{A\subset\Lambda_N\\ |A|\geqslant M}} \varepsilon^{|A|}\,(e^{-8}(1+\frac{1}{\varepsilon}))^{|A|}\,\frac{Z^{0,+}_{\Lambda_N\setminus A}}{Z_N^{0,+,\varepsilon}}\,\mu^{0,+}_{\Lambda_N\setminus A}\left(e^{-\mathcal{X}(\phi)}\right)\,.$$

Clearly,

$$\mu^{0,+}_{\Lambda_N\setminus A}\left(e^{-\mathcal{X}(\phi)}\right) \geqslant e^{-c_1(|\partial\Lambda_N|+|A|)}\,\mu^{0,+}_{\Lambda_N\setminus A}(\mathcal{X}(\phi)\leqslant c_1|\partial W|)\,.$$

The conclusion will follow as before, once we prove that this last probability is bounded from below by, say, 1/2. Using Markov inequality, we get

$$\mu^{0,+}_{\Lambda_N\setminus A}(|\partial W|^{-1}\mathcal{X}(\phi)>c_1)\leqslant \frac{\mu^{0,+}_{\Lambda_N\setminus A}(|\partial W|^{-1}\mathcal{X}(\phi))}{c_1}\,.$$

Since it follows from [10] (Lemma 2.1) that there exists an absolute constant c_2 such that $\mu^{0,+}_{\Lambda_N\setminus A}(|\partial W|^{-1}\mathcal{X}(\phi))\leqslant c_2$, the result follows by taking c_1 large enough.

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